Demonstration of Novel Stimulation and Near Wellbore Damage Removal in Gas Storage Wells

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NOTICE

ABSTRACT

Many gas storage wells are gradually damaged through normal operations and continue to lose deliverability every year. This reduces the peak volume available from state resources, while increasing the product cost as more gas is purchased off interstate pipelines. Underground gas storage operators spend millions of dollars annually in an effort to maintain deliverability levels.

Recent studies have reviewed deliverability enhancement techniques routinely used in storage industry. The primary objective of this study is to evaluate potential new stimulation technology that can be used to maintain and improve deliverability in UGS wells.

Three novel stimulation techniques in gas storage were evaluated using analytic solutions, simulation models, and empirical field data. Estimates of deliverability improvement expected from implementing these techniques were also generated. The applicability, advantages, and disadvantages of each of the stimulation methods are also discussed.

The first technology evaluated was the use of a large diameter underreamer to increase the wellbore diameter in the productive zone. The second technology evaluated was stimulation of a well by drilling four horizontal laterals using water jet technology. The third stimulation technique investigated was a propellant technology called the GasGun™ technology. It involves the use of a slow burning propellant to create multiple fractures in the reservoir.

Estimates of minimum, maximum and average deliverability improvements expected from each technology were generated. It was concluded that an average increase of 160% can be reasonably expected from the propellant technology, an average deliverability increase of 100% may be expected using large-diameter underreamer technology. The horizontal laterals technology shows the highest effectiveness with an average deliverability increase of 650%. However, based on our cost-benefit analysis using the cost per incremental production indicator, the GasGun™ propellant technology was ranked highest amongst the three stimulation techniques and the large diameter underreamer was ranked lowest. This is primarily due to lower deliverability improvements and higher cost (mainly workover costs) associated with the underreamer technology.

Some of the input parameters such as cost of stimulation and stimulation results data used in the economic analysis fluctuates among different operators. In order to produce updated and usable results, a simple spreadsheet tool was developed as part of this study to aid UGS operators' selection of the most appropriate technology to cost effectively improve UGS well deliverability in their specific fields.

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EXECUTIVE SUMMARY

The underground gas storage (UGS) industry uses over 15,000 wells in about 400 reservoirs to store and withdraw natural gas and therefore significantly contributes to the gas supply in the United States[1]. Previous analyses indicate that many gas storage wells show a loss of deliverability each year due to various damage mechanisms[2], requiring UGS operators to spend millions of dollars annually in an effort to simply maintain deliverability levels[3].

Recent studies[4,5,6] reviewed completion and deliverability enhancement techniques used in the storage industry, identified specific damage mechanisms present in storage reservoirs, established procedures for damage mechanism identification, and measured the effectiveness and longevity of various stimulation technologies currently employed by UGS operators. These and other recent gas storage studies highlight the obvious need to identify and test new stimulation techniques that can be successfully applied in UGS wells.

The primary objectives of this study are aimed at evaluating potential new stimulation technology that can be used to maintain and improve deliverability in UGS wells. The original scope of work proposed for this study included the following major tasks:

- Theoretically evaluate three novel stimulation techniques in underground gas storage fields and estimate anticipated deliverability improvements resulting from implementation of the following new/novel technologies:
    - Under-reaming
    - Jetted horizontal laterals
    - Propellant stimulation (GasGun™)
- Conduct pilot field test for the above technologies where possible
- Develop simple, user-friendly tools to evaluate the economics of implementing the above technologies

Results of our theoretical evaluation of the stimulation techniques listed above are summarized in **Table 1** below.

Table 1. Summary of Theoretical Study Results

Deliverability Stimulation Method	Minimum Deliverability Increase (%)	Maximum Deliverability Increase (%)	Average Deliverability Increase (%)	Minimum Unit Cost of Deliverability Improvement ($/scfd)	Maximum Cost of Deliverability Improvement ($/scfd)	Average Unit Cost of Deliverability Improvement ($/scfd)
Acid Job	-50	4500	275	0.07	0.36	0.19
Frac Job	10	1500	445	0.22	0.82	0.37
GasGun	-93	900	155	0.17	0.75	0.26
Jetted Horizontals	100	1567	660	0.18	0.66	0.38
Underreaming	10	350	120	0.19	1.67	0.69

Due to difficulties securing the participation of industry operators willing to implement these three technologies in the field, we were limited to planning a pilot study only for the GasGun^{TM} technology. Unfortunately, unforeseen operational complications that occurred while field testing the pilot study wells stimulated with the GasGun^{TM} rendered the tests inconclusive. We abandoned further field stimulations and testing because these additional costs were not included in the operators' annual budget.. Notwithstanding these challenges, the large amount of publically available pre- and post-stimulation test data available for the GasGun^{TM} made it possible to draw statistically significant conclusions concerning the effectiveness of GasGun^{TM} stimulations for a wide variety of lithology, locations, fluid types, and well types.

A simple, user-friendly, EXCEL-based tool was developed as part of this study to aid UGS operators' select the most appropriate technology to cost effectively improve well deliverability in their specific fields. **Table 2** shows example output from this tool, allowing operators to input local costs and success rates for each stimulation type, which are used to estimate deliverability increases and unit costs.

Table 2. Example Output of Stimulation Selection Tool

Stimulation Type	Stimulation Cost ($)	Probability of Success %	Est'd % Deliverability Increase	Pre-Stimulation Deliverability (mscfd)	Post-Stimulation Deliverability (mscfd)	Increase in Deliverability (mscfd)	Cost per Incremental Deliverability ($/scfd)
Acid Job	$ 16,000	75%	275%	30	112.50	82.50	0.19
Frac Job	$ 50,000	80%	445%	30	163.50	133.50	0.37
Gas Gun	$ 12,000	90%	155%	30	76.50	46.50	0.26
Jetted Laterals	$ 75,000	66%	660%	30	228.00	198.00	0.38
Large Dia UR	$ 25,000	75%	120%	30	66.00	36.00	0.69

(shaded)	Input
(blank)	Calculated

DESCRIPTION OF STUDY

Normal operation of many gas storage wells result in increasing damage and continual reduction in the deliverability of the wells each year. This reduction in deliverability affects the cumulative gas volume available from State resources and also increases the product cost. Consequently more gas is purchased from the interstate pipelines. Underground gas storage operators spend a significant percentage of their field budgets annually in an effort to simply maintain deliverability levels[7].

Three novel stimulation techniques were considered for analysis with an objective of evaluating the merits and anticipated deliverability of each technique as applies to the UGS industry. The first technology involves the use of a large diameter underreamer to increase the wellbore diameter in the productive zone. The second technology was stimulation of a well by drilling four horizontal laterals using water jet technology. The third technology investigated was a propellant technology called GasGun™, which involves the use of a slow burning propellant to create multiple fractures in the reservoir.

Each of the technologies investigated has unique methods of damage removal or bypass to enhance well production. In order to evaluate the treatment types, the effectiveness of the stimulation methods were considered. The effectiveness of the stimulation treatment is a quantitative indication of the deliverability increase as a result of stimulating the well, and was defined as the percentage increase in the deliverability of the well that occurs after the well has been stimulated:

$$\text{Effectiveness} = \frac{\text{Post-Stimulation Deliverability) - (Pre-Stimulation Deliverability)}}{\text{(Pre-Stimulation Deliverability)}}$$

Evaluation of the large diameter underreaming tool was done by first creating a base case scenario with defined reservoir and well properties typical of gas storage facilities. The effectiveness of the tool was then obtained by calculating the increased deliverability associated with increasing the initial diameter of the base case well.

Evaluation of the jetted horizontal lateral technology was done by numerically simulating the effect of drilling four laterals of varying lengths in the base case well. The effectiveness of the technology was calculated using simulation model results. The effect of various reservoir and horizontal well design parameters were considered and the increase in deliverability associated with variations in these factors was investigated. Pre- and post-stimulation results from the application of this technology were available in public databases, and this data was used to calibrate results obtained from the simulation model.

The field test of the GasGun™ technology was planned on three wells in the Heneoye gas storage field, located in Ontario County, New York. Unfortunately, complications related to field testing in the pilot study wells occurred, so pilot test results for this technology were inconclusive. However, the availability of large amounts of public data (pre- and post-stimulation test results) for the GasGun™ stimulations made it possible to statistically evaluate the effectiveness of this technology. The pilot test information and a description of the difficulties encountered during pilot testing are included in the discussions section of this study.

A description of the three novel technologies, their applicability, advantages, and disadvantages are also included in the discussion section of this study.

CONCLUSIONS AND RECOMMENDATIONS

The three stimulation methods investigated can be effectively applied toward the improvement of gas deliverability in UGS wells. Each of the technologies investigated have unique methods of damage removal or bypass to enhance production in wells. The expected percentage improvement ranges from 80% to 650%.

A cost benefit analysis using the cost per incremental production indicator shows that GasGun™ propellant technology is ranked highest amongst the three stimulation techniques while the underreamer is the lowest. This is due to the low deliverability improvement and high cost (mostly workover costs) associated with the underreamer technology.

The expected improvements obtained from the three novel technologies are comparable to conventional stimulation techniques such as hydraulic fracturing and acidizing. When acidizing and hydraulic fracturing stimulation methods are included in the cost benefit analysis using the cost per incremental production indicator, the GasGun™ technology and the acidizing method have very close results and can be considered as equally ranked.

Similarly, a hydraulic fracturing job can be considered as equally ranked with a jetted horizontal lateral stimulation treatment because of the close values obtained with the indicator used. Nonetheless, Jetted horizontal laterals remain the most expensive treatment but it has the highest deliverability for the three technologies investigated.

Conclusions and recommendations related to each of the three stimulation technologies examined are summarized below.

LARGE DIAMETER UNDERREAMING

Conclusions

Application of the technology is limited to open-hole completions or prior to the casing of the well. The simulation model shows that improvements in deliverability range from a 30% to 300%.

The results of the simulation show that one of the major factors that affect the expected deliverability increase is the ratio of the final diameter to the initial diameter. As much as a 100% increase in deliverability may be expected when the initial pre-stimulation diameter is tripled. Hence, the pre-stimulation gas flow rate is an important factor to be considered when considering an underreaming stimulation job. The benefit of an underreaming job is greater for a well with high flow rates because the higher wellbore area available for flow helps reduce the skin generated due to non-darcy effects.

The cost benefit analysis determined the cost per incremental deliverability, and shows that the underreaming technology has a value of 0.69 \$/scfd compared to a value of 0.37 \$/scfd obtainable from conventional fracturing. In essence, the underreamer may cost more and yet give a lower deliverability than a conventional hydraulic fracture.

The cost associated with the underreamer is greatly increased because of the need to have a workover rig available for the stimulation.

Recommendations

The large diameter underreamer is best applicable as part of an initial completion and drilling plan for a new well. The cost of the stimulation can be controlled by incorporating other workover operations. An underreamed well may also be hydraulically fractured or acidized to further increase deliverability.

HORIZONTAL LATERALS

Conclusions

Horizontal laterals can effectively bypass the near wellbore damage in a well and increase wellbore contact with the reservoir. Up to four laterals may be drilled in different orientations relative to the maximum and minimum stress. This helps to effectively exploit reservoir anisotropy and heterogeneity.

The horizontal laterals technology shows a high effectiveness with an average of 650% increase in deliverability. The simulation model shows that improvements in deliverability range from a 300% increase to 1600% increase while data obtained from stimulations performed in the field show improvements in deliverability ranging from 80% to 1500% increase.

The length of the horizontal laterals and the net height of the pay zone have the greatest effect on the deliverability. Conversely, deliverability is least sensitivity to the ratio of vertical permeability to horizontal permeability (kv/kh ratio).

There is a slight reduction in the deliverability of a stimulated well in a reservoir with lower kv/kh ratio in a low permeability reservoir. Permeability anisotropy is therefore not regarded as a critical factor to consider in a lower permeability reservoirs.

It was also concluded from the reservoir permeability and thickness sensitivity studies that a reservoir with lower permeability obtains a higher advantage to stimulation using the jetted horizontal laterals. The jetted horizontal laterals also have better stimulation responses in thin reservoir than in thicker reservoirs.

The cost benefit analysis determined the cost per incremental deliverability, and showed that the horizontal lateral technology has a value of 0.38 $/scfd as compared to a value of 0.37 $/scfd obtainable from a conventional fracture. In essence, the horizontal laterals stimulation usually costs more than a conventional hydraulic fracture but a higher increase in deliverability can be expected.

<u>Recommendations</u>

Shorter horizontal laterals are recommended in higher permeability formations while longer laterals are recommended in lower permeability formations. This stimulation technique can work well in highly natural fractured reservoirs by connecting the fractures to the wellbore. Depending on the type of formation, acidizing of the horizontal laterals may be considered to further increase deliverability.

PROPELLANT TECHNOLOGY - GASGUN™

<u>Conclusions</u>

The GasGun™ technology appears to have an average effectiveness of 160% in deliverability of gas wells. The quantitative analysis shows that improvements in deliverability range from a 100% increase to 900% increase. There is an 80% chance of stimulation success with the GasGun™ technology.

Quantitative analysis of field data indicates that the GasGun™ is more effectiveness in oil producing formations than in gas producers. However, GasGun™ technology has been found to be very effective in gas bearing coal formations.

The examination of deliverability by depth suggests that the GasGun™ is more effective in wells with a depth less than 2500 feet. There appears to be a higher stimulation benefit for open hole completions rather than for cased hole completions. However, the perforation length does not seem to have a noticeable impact on the effectiveness of the GasGun™ treatment.

The cost benefit analysis done using a cost per incremental deliverability shows that the GasGun™ technology has a value of 0.26 $/scfd as compared to a value of 0.37 $/scfd obtainable from a conventional fracture. In essence, the GasGun™ stimulation usually costs less than a conventional hydraulic fracture but a much lower increase in deliverability can be expected.

<u>Recommendations</u>

Unfortunately, we were unable to obtain sufficient data from the controlled field pilot studies that were performed in a gas storage field to evaluate the effectiveness of the technology. Controlled field tests are still recommended to provide actual performance data on comparison of pre-stimulation and post stimulation data. The possibility of operational failures and associated costs should be taken into account when planning the further field tests

Propellant technology is recommended when minimal vertical growth out of pay is desired. There is also very little formation damage cause by incompatible fluids. The propellant technology can also be used along with an acidizing treatment or a hydraulic fracture treatment to further improve the deliverability of the well.

RESULTS

In order to accomplish the objectives of the project, the three stimulation methods were compared with the conventional methods of hydraulic fracturing and matrix acidizing treatments. Data showing the effectiveness of matrix acidizing and hydraulic fracturing is obtained from a prior GRI investigation by Schlumberger DCS[7].

Recall that the effectiveness of the stimulation treatment is a quantitative indication of the deliverability increase as a result of stimulating the well, and was defined as the percentage increase in the deliverability of the well that occurs after the well has been stimulated:

$$\text{Effectiveness} = \frac{\text{Post-Stimulation Deliverability}) - (\text{Pre-Stimulation Deliverability})}{(\text{Pre-Stimulation Deliverability})}$$

Figure 3-1 below illustrates the estimated average effectiveness of different treatment methods for underground gas storage wells. Subsequent plots in this section show the stimulation methods in the same order for ease of comparison. Effectiveness of acidizing and fracturing stimulations used in the comparisons below were reported in a prior GRI study[7].

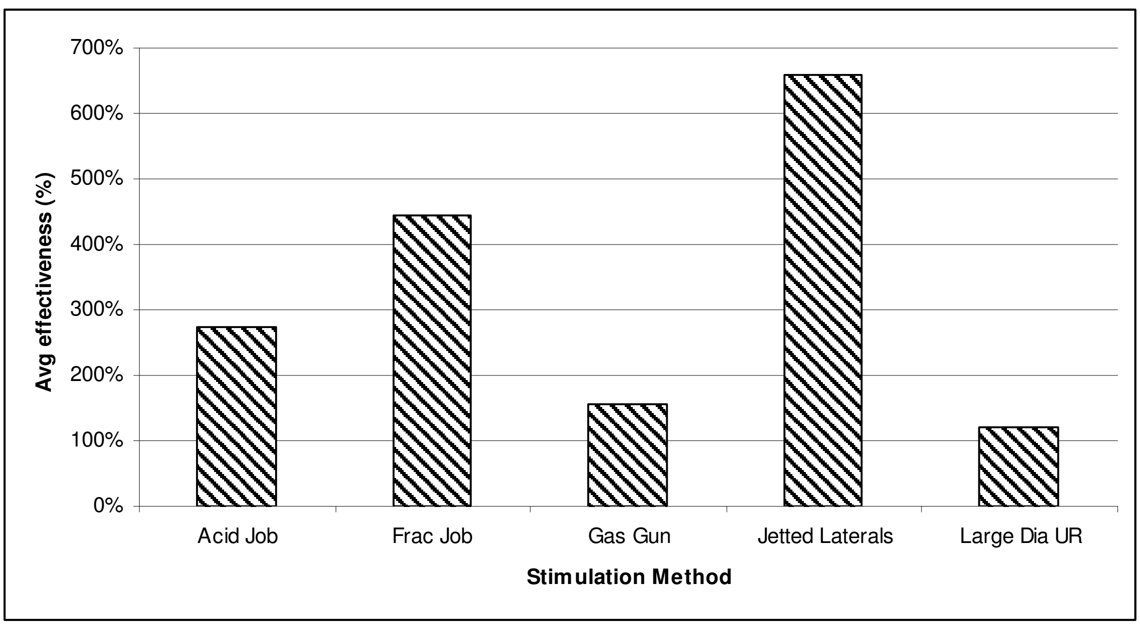

Figure 3-1 Comparison of deliverability improvements for different stimulation methods

The average effectiveness of the jetted laterals stimulation used in this analysis was obtained from a reservoir simulation model having four horizontal laterals of 50 and 100 feet in length and a diameter of 1 inch. The effectiveness values obtained from reservoir simulation were calibrated with average effectiveness values obtained from field data sample of 15 wells that were treated using the jetted laterals technolog[8]. The average effectiveness of the large diameter underreaming technology was calculated using an analytical solution[9] of a well and reservoir with the same parameters used in the jetted laterals simulation. The diameter of the base case well was increased from 8 inches to 96 inches. The GasGun™ effectiveness was obtained from the analysis of publically available GasGun™ stimulation data in gas producing reservoirs[10, 11].

In an effort to determine the variation in treatment success, we also plotted the minimum, maximum and average values of effectiveness for all treatment types. (**Figure 3-2**).

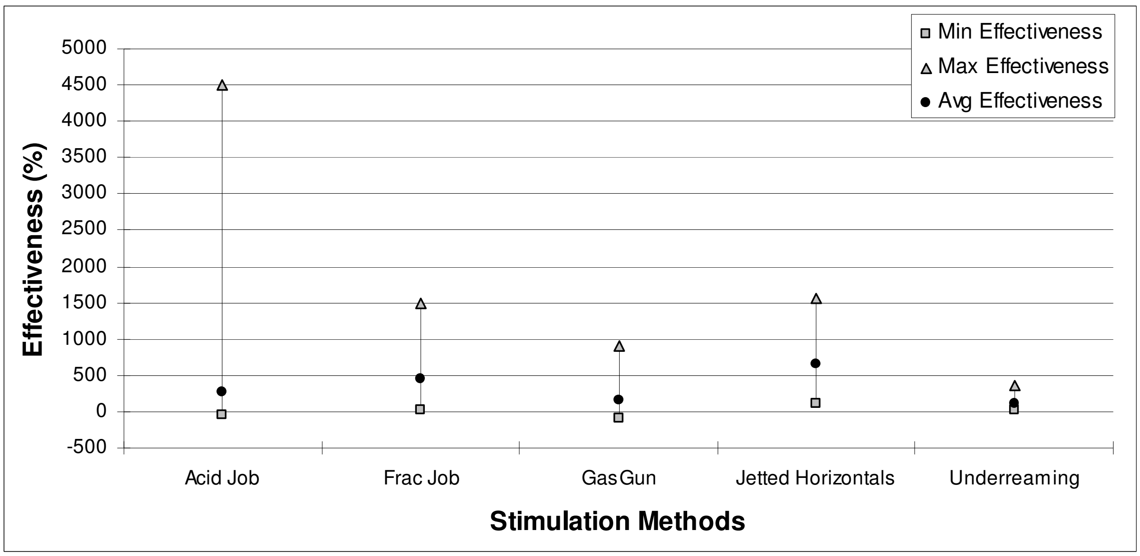

Figure 3-2. Min, Max and Avg Effectiveness for Treatment Types

Amongst the three stimulation techniques investigated, the jetted horizontal laterals technology showed the highest effectiveness, primarily due to the greater amount of reservoir contact created using this method.

Figure 3-3 shows a comparison between the estimated costs of each of the stimulation treatment methods. This plot suggests that the GasGun™ stimulation technology is the least expensive method of stimulation. The jetted horizontal treatment is the most expensive and could cost up to 7 times the cost of a GasGun™ treatment for a single stage.

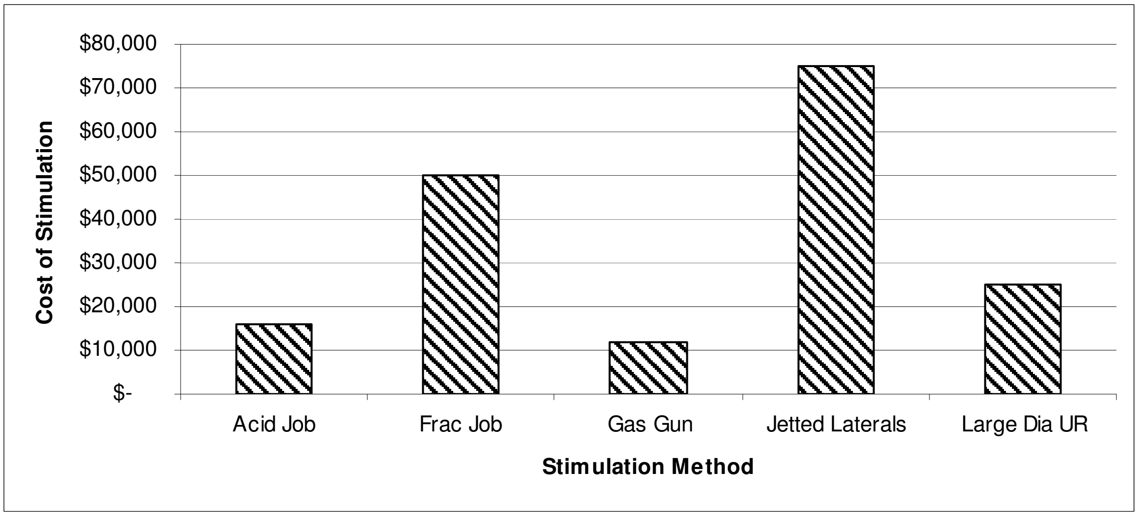

Figure 3-3. Comparison of stimulation cost of technologies

Stimulation costs may vary by the design of the job, economic environment, company providing the service, and the type of stimulation is being performed. Even the cost of the same stimulation type may fluctuate among different operators. This occurs due to differing field characteristics, well completions, proximity to service companies, etc. However, the costs of each of the methods are estimated based on the average costs for stimulating a single stage in a well in the current economic climate.

In an effort to determine the variation in treatment costs, we also plotted the minimum, maximum and average costs for a single stage for the various treatment types. (**Figure 3-4**).

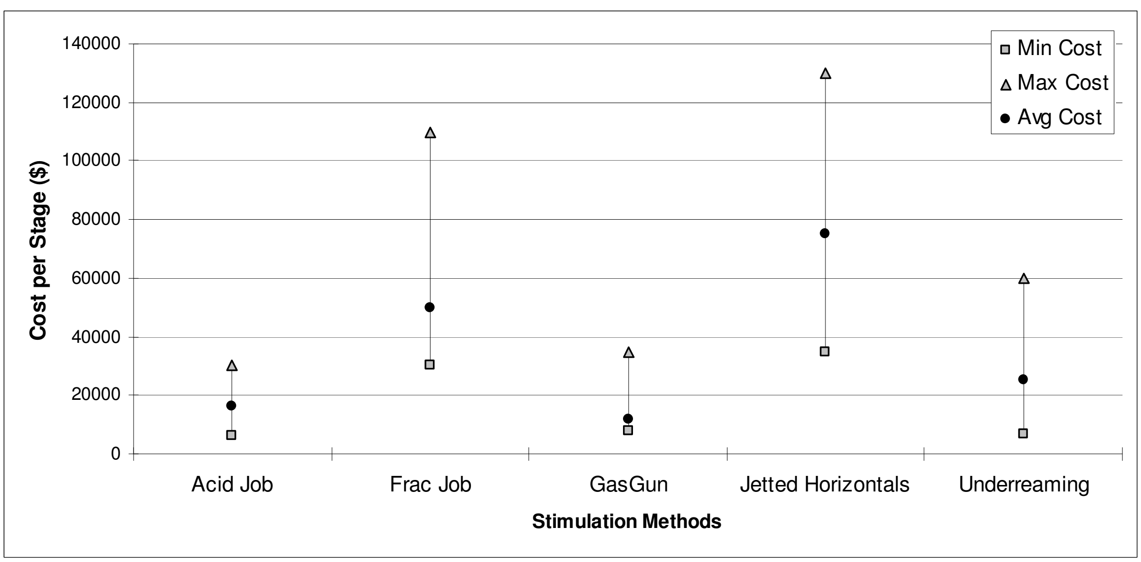

Figure 3-4. Min, Max and Avg Cost of Stimulation for a Single Stage

Jetted horizontal laterals remain the most expensive treatment but have the highest deliverability for the three technologies investigated.

The cost associated with the large diameter underreaming technology is high in comparison with its benefits because a workover rig is needed for the service. If the underreaming is done during drilling or in conjunction with other workover operations, the effective cost may be significantly reduced. Also, the cost associated with underreaming is done for the whole productive zone and the charge was not broken into stages as in other stimulation methods. In an attempt to quantify underreaming cost per stage, the total average cost of the underreaming service was divided by an average number of stages.

In order to effectively compare successfulness of the stimulation techniques, a method defining the cost per incremental deliverability was used. **Figure 3-5** shows the cost per incremental deliverability of the various stimulation methods. Stimulation methods having lower cost per incremental deliverability are more successful.

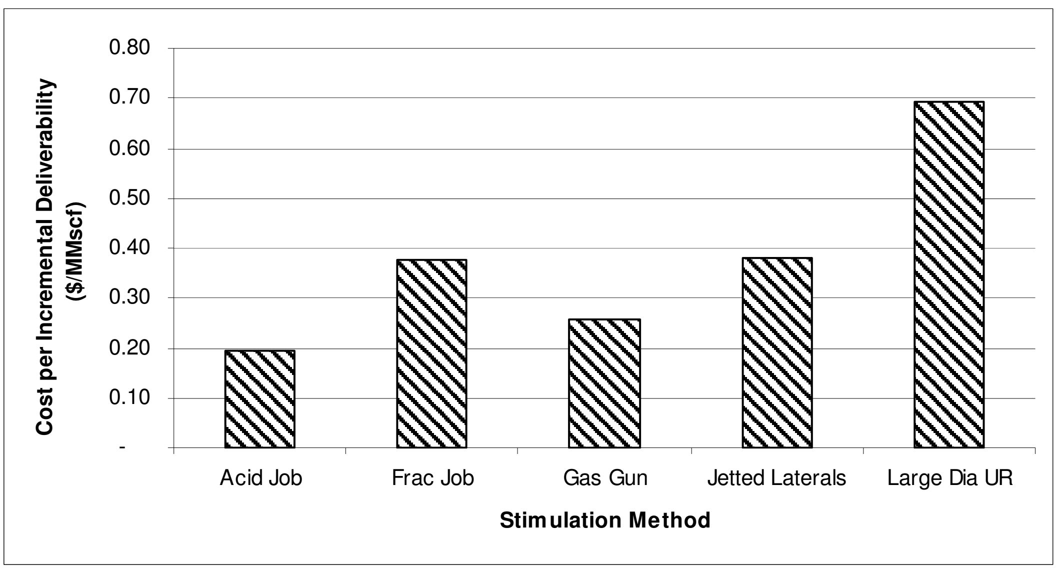

Figure 3-5. Cost per Incremental Deliverability by Stimulation Type

In an effort to determine the variability in cost per incremental deliverability indicator, we also plotted the minimum, maximum and average ranking for the various treatment types (**Figure 3-6**).

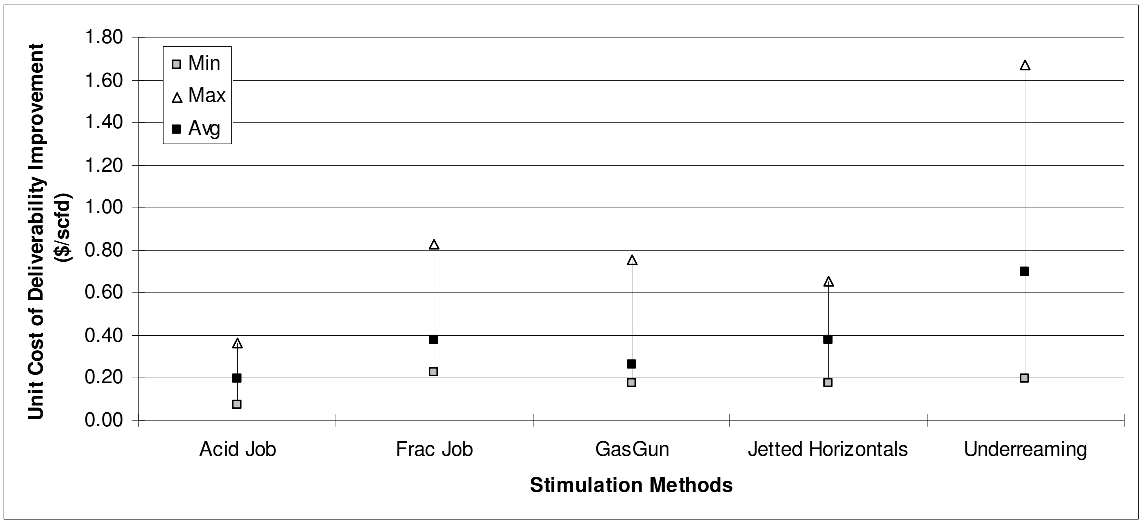

Figure 3-6 Min, Max and Avg Unit Cost of Deliverability Improvement

Of the three methods under investigation, the GasGun™ was the more successful technique using this method of ranking. However, as previously mentioned, if the cost of the underreaming is shared with a different workover operation, it could also rank closely with the GasGun™.

The parameters used in this study tend to vary with time and economic seasons. Therefore, a tool was developed to help compare the technologies and aid stimulation type selection as input parameters are periodically updated. The tool was developed and tested using EXCEL™. Using data supplied from operators, the cost per incremental deliverability indicator can be generated using this tool. **Table 3-1** is an example of the input and output generated using the tool.

Table 3-1. Output of Stimulation Selection Tool

Stimulation Type	Stimulation Cost ($)	Probability of Success %	Est'd % Deliverability Increase	Pre-Stimulation Deliverability (mscfd)	Post-Stimulation Deliverability (mscfd)	Increase in Deliverability (mscfd)	Cost per Incremental Deliverability ($/scfd)
Acid Job	$ 16,000	75%	275%	30	112.50	82.50	0.19
Frac Job	$ 50,000	80%	445%	30	163.50	133.50	0.37
Gas Gun	$ 12,000	90%	155%	30	76.50	46.50	0.26
Jetted Laterals	$ 75,000	66%	660%	30	228.00	198.00	0.38
Large Dia UR	$ 25,000	75%	120%	30	66.00	36.00	0.69

(shaded)	Input
(unshaded)	Calculated

This tool was also modified to create a range of results such that a risk factor can be applied to the ranking of the different stimulation technologies. **Table 3-2** is an example of the output generated using the stimulation selection range tool.

Table 3-2. Output of Stimulation Selection Range Tool

Deliverability Stimulation Method	Minimum Deliverability Increase (%)	Maximum Deliverability Increase (%)	Average Deliverability Increase (%)	Minimum Unit Cost of Deliverability Improvement ($/scfd)	Maximum Cost of Deliverability Improvement ($/scfd)	Average Unit Cost of Deliverability Improvement ($/scfd)
Acid Job	-50	4500	275	0.07	0.36	0.19
Frac Job	10	1500	445	0.22	0.82	0.37
GasGun	-93	900	155	0.17	0.75	0.26
Jetted Horizontals	100	1567	660	0.18	0.66	0.38
Underreaming	10	350	120	0.19	1.67	0.69

DISCUSSION

UNDER-REAMING TECHNOLOGY

The under-reaming technology incorporates the use of a drilling tool as a mechanical means to effectively increase the wellbore openhole diameter, thereby increasing the open surface area and wellbore volume significantly. The cost of drilling a large diameter wellbore for the whole depth of a well would be extremely expensive. The large diameter under-reaming tool allows the enlargement of only the productive zone.

The large diameter under-reaming tool can also be used as a stimulation mechanism to remove near wellbore formation damage by cutting out some or all of the near wellbore region. If the effect of the enlarged diameter is not considered, the formation damage removal only occurs if the formation damage done during the workover is less that the original drilling damage.

<u>Description of Technology</u>

The large diameter under-reaming tool is attached at the end of a drill string and initially cuts using centrifugal force when rotation is applied to the drill string. The drill string weight can be added subsequently if desired. The large diameter under-reaming tool can usually cut up or down without circulation. **Figure 4-1** shows a large diameter under-reaming tool cutting downwards while **Figure 4-2** shows a large diameter under-reaming tool cutting upward.

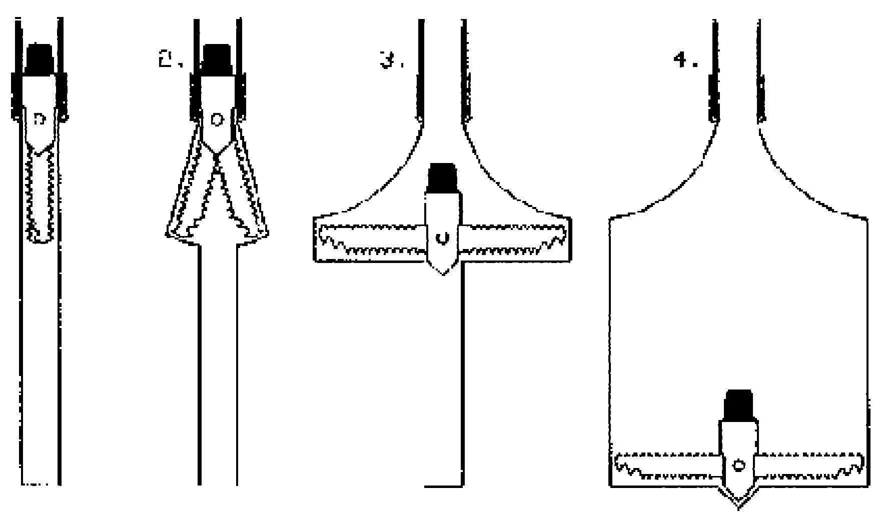

Figure 4-1. Large Diameter Under-Reaming Tool Cutting Down

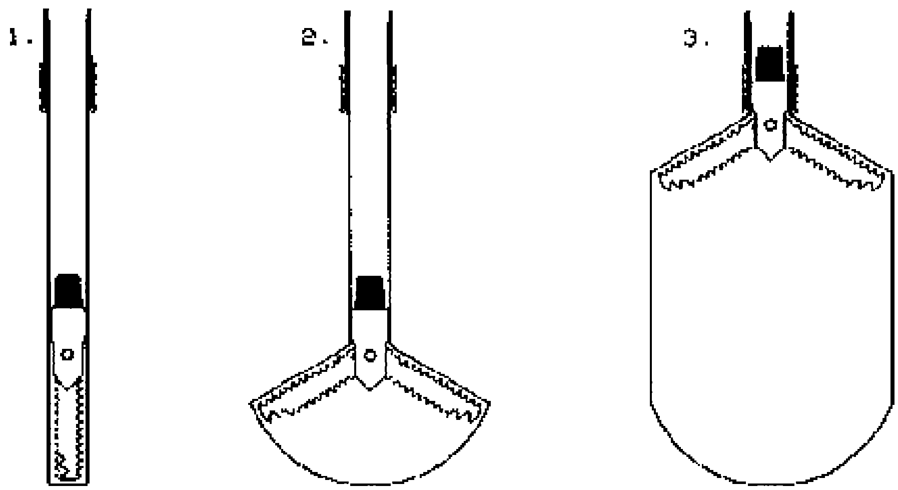

Figure 4-2. Large Diameter Under-Reaming Tool Cutting Down

The tool has various closed and open diameters and can create a cavity with a diameter up to 8 feet. However the hardness of the formation may limit the diameter created.

Application of Technology

The large diameter under-reamer is applicable in oil and gas production wells as well as underground storage wells. Some of the possible applications of the tool include

- Creation of cavern for horizontal and multilateral drilling
- Creation of larger borehole volume for increased sump capacity
- Reducing sand and fines production
- Cleaning of the casing

Advantages of Technology

The use of the large diameter under-reamer to increase the diameter of the wellbore has some inherent advantages over other methods of stimulation and can be combined with other methods of stimulation. Some of the added advantages that are obtained while using the under-reamer in underground gas storage include:

- Increased formation to wellbore interface
- Exponential increase in borehole volume
- Intersection of natural fractures

The under-reamer is a low-cost solution if used during the drilling phase of the well. However if the under-reamer is used on an actively producing well, the workover costs may be higher than conventional fracturing and acidizing jobs.

Results of Evaluation

An initial evaluation of the effect of an increase in diameter on the gas flow rate was made by investigating the sensitivity of the gas flow rate to changing wellbore diameter in the pseudosteady state Darcy's law equation (note that this analysis ignores non-darcy flow effects). As shown in **Figure 4-3** and **Table 4-1** below, the increase in wellbore diameter causes a corresponding increase in production. Note that if the diameter is doubled, the gas rate increases by 10 to 16% regardless of the initial base case diameter. However, increasing the wellbore diameter from 8 inches to 8 feet (a 12 fold increase) would produce a 52% increase in gas production.

Table 4-1. Table showing Sensitivity of Gas Rate to Wellbore Diameter

Wellbore Diameter (ft)	Gas Rate (MMscf/d)	% Improvement
0.66	15.4	Base Case
1	16.3	6
2	18.2	18
4	20.5	33
6	22.1	43
8	23.4	52

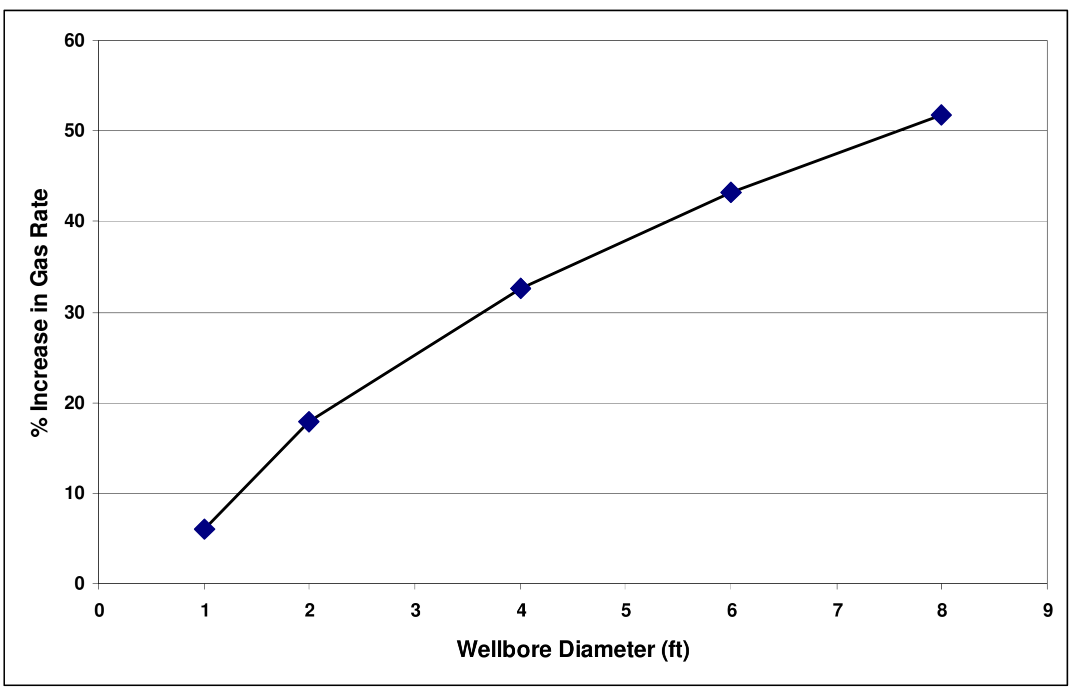

Figure 4-3. Sensitivity of Wellbore Diameter to Gas Rate

A more rigorous solution that considers both laminar and the turbulent flow effects was then utilized. The non-darcy skin effect was included in the solution using the Forchheimer equation. The non-darcy skin effects occur mainly due to changes in the velocity of the fluid in the near wellbore area.

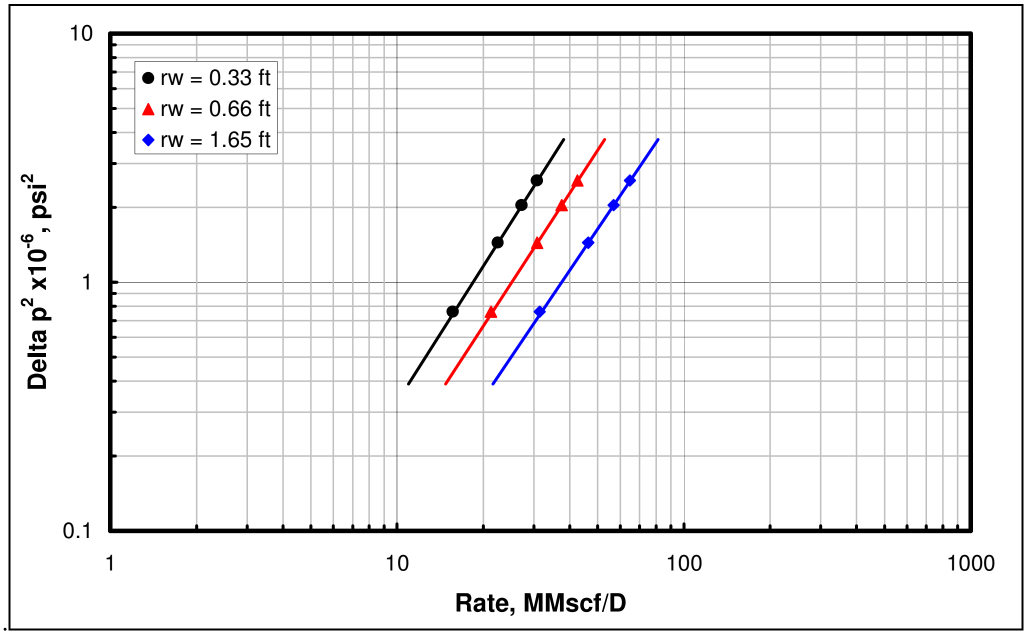

Figure 4-4. Effect of increasing wellbore diameter

Figure 4-4 shows the synthetic backpressure plots generated using the more rigorous solution that considers both laminar and the turbulent flow effects (i.e., includes effects of under-reaming on both the Darcy and non-Darcy components of pressure drop). **Figure 4-4** shows that increasing the wellbore diameter causes a corresponding increase in gas flow rate at a constant delta-pressure squared value. The production increase achieved by doubling the wellbore diameter ranges from 20% to 60%. When the wellbore diameter is increased from 8 inches to 40 inches, a 100% to 150% increase in production is expected.

JETTED HORIZONTALS

The jetted horizontals technology involves the use of water-jet technology to stimulate a well by drilling up to four multilateral horizontal channels. The water-jet technology is applied primarily in producing wells but can also be applied in gas storage wells. This technology can drill up to four, 2 inch diameter, 500 feet horizontal channels in both openhole and old cased hole wells. Minimal water is used to cut the channels, thus reducing the potential to further damage the wells.

This study investigates the effect of the horizontal laterals on the gas rate theoretically by using a reservoir simulation model.

<u>Description of Technology</u>

High pressure and high velocity streams of water are used to cut up to four horizontal laterals with lengths of up to 500 feet. The horizontal laterals can have a diameter from 0.5 to 2.0 inches.

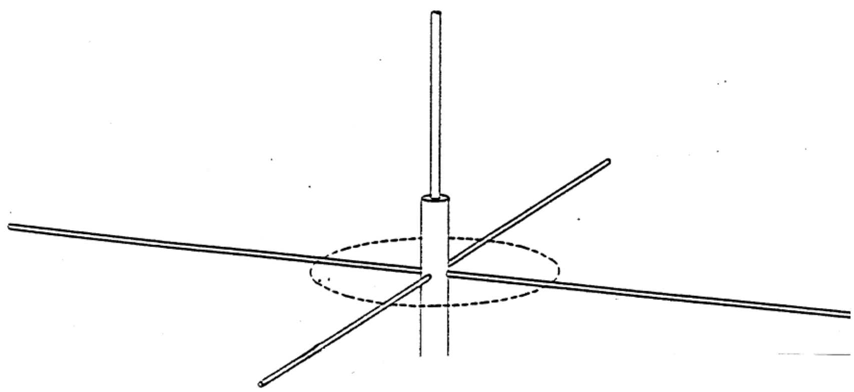

Figure 4-5 Multiple Horizontal laterals

<u>Application of Technology</u>

The drilling of laterals using the water-jet technology has been used in oil and gas producer wells to bypass near wellbore damage and to increase reservoir contact and productivity. The technology has also been used in water injection wells to increase water injection rates. The technology can also be used in the underground gas storage industry to stimulate the storage wells thereby increasing the deliverability.

<u>Advantages of Technology</u>

Some of the advantages of the water-jet technology include:

- Formation damage is bypassed by the horizontal laterals
- Increased reservoir contact with the wellbore
- Minimal amount of fluid used to create horizontal laterals reducing further damage
- No vertical growth out of pay
- Exploits reservoir anisotropy and heterogeneity

Results of Evaluation

The reservoir simulation accounts for formation damage at the sandface of in each of the laterals and also considers the non-Darcy flow effect. **Figure 4-6** shows an illustration of the simulation model assumptions.

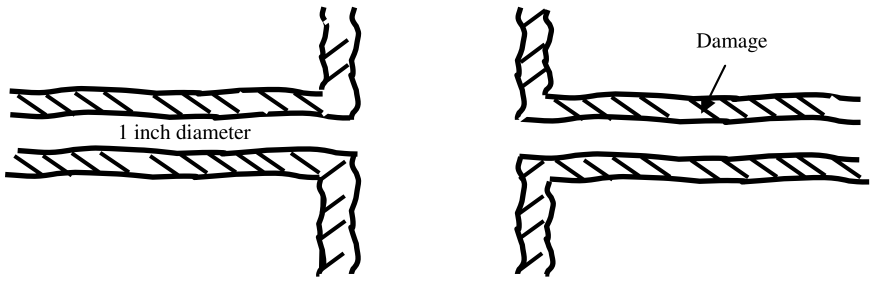

Figure 4-6. Schematic of Pressure Drop in Simulation Model

Simulation runs were conducted on a well with four laterals. The simulation runs were classified into two formation types: lower permeability (5 md) and higher permeability (50 md). For each formation classification, two values of vertical permeability anisotropy, height of the pay, and length of the laterals were used, as shown in Table 4-2. The following reservoir parameters were held constant:

- Drainage area = 320 acres
- Specific gravity = 0.58
- Reservoir temperature = 100 ^{0}F
- Reservoir pressure = 1000 psia
- Flowing bottomhole pressure = 200 psia
- Porosity = 20 %
- Number of laterals = 4
- Diameter of lateral = 1 inch
- Mechanical skin in lateral = 25

Table 4-2. Variables Used in Model Simulations

	LOW	Hi
k_v/k_h	0.1	0.5
h (ft)	10	30
L_h (ft)	50	100

Effect of Anisotropy (Kv/Kh). In this case, four horizontal laterals of 100 feet each were modeled in a vertical well drilled in a reservoir with permeability of 5 md and a productive height of 30 ft. The effect of varying the permeability anisotropy (Kv/Kh) from 0.1 to 0.5 was observed. **Figure 4-7** shows the percentage increase in production when the well is stimulated with the jetted horizontals for both permeability anisotropies.

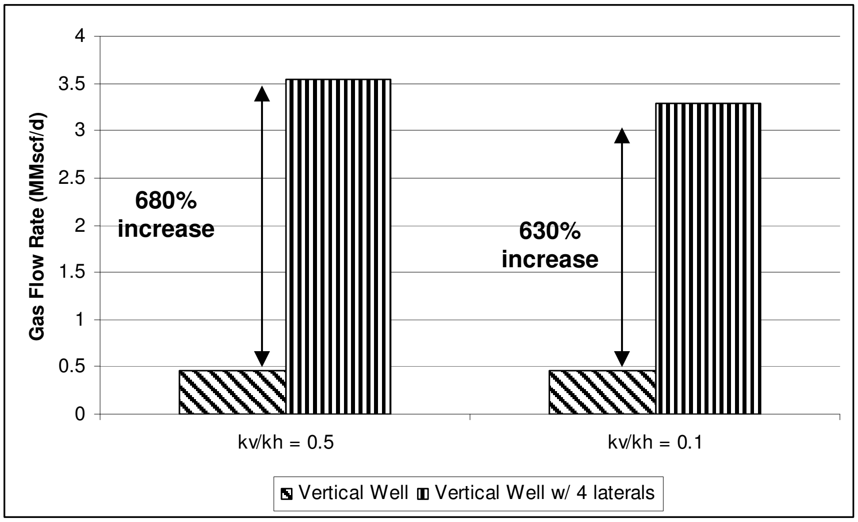

Figure 4-7.Effect of varying Kv/Kh on stimulation results

Although there is a slight reduction in the deliverability of the stimulated well in a reservoir with lower kv/kh ratio, the kv/kh ratio is not a critical factor to consider in a lower permeability formations.

Effect of Formation Permeability. In this case, four horizontal laterals of 100 feet each were modeled in a vertical well with a productive height of 30 feet. The effect of varying the formation permeability from 5 md to 50 md is observed. **Figure 4-8** shows the percentage increase in production when the well is stimulated with the jetted horizontals for both cases.

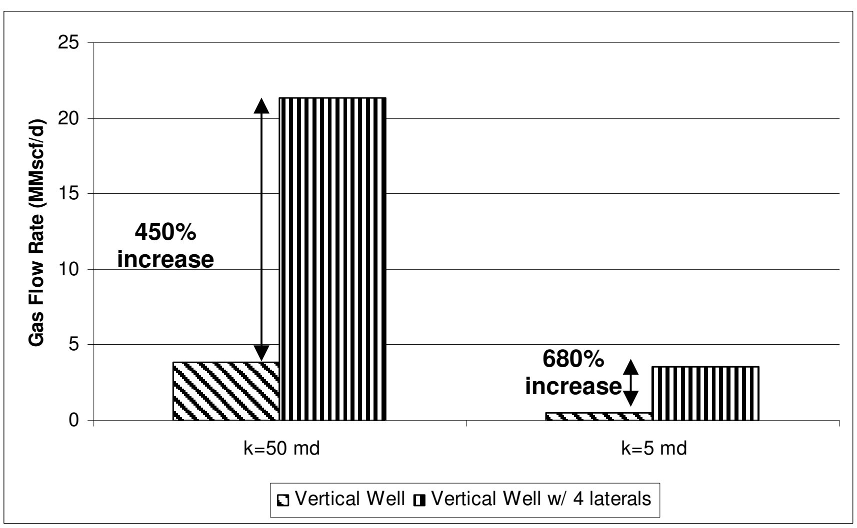

Figure 4-8.Effect of varying reservoir permeability on stimulation results for h=30 ft

There is a higher percentage increase in gas rate obtained from a jetted horizontal stimulation in the lower permeability formation than that obtained from a higher permeability formation. The reservoir with a lower permeability obtains a higher advantage to stimulation. Although the lower permeability formation shows a higher *percentage* increase in gas rate, the higher permeability formation yields significantly higher incremental gas rate values, suggesting that both the percentage and absolute value of gas rate increases should be considered when evaluating study results.

Effect of Productive Height. In this case, four horizontal laterals of 100 feet each are modeled in a vertical well with a productive height of 10 feet in order to compare it to the previous case where a height of 30 feet is used. **Figure 4-9** shows the percentage increase in production when the well is stimulated with the jetted horizontals for a low permeability and a high permeability reservoir with different formation heights.

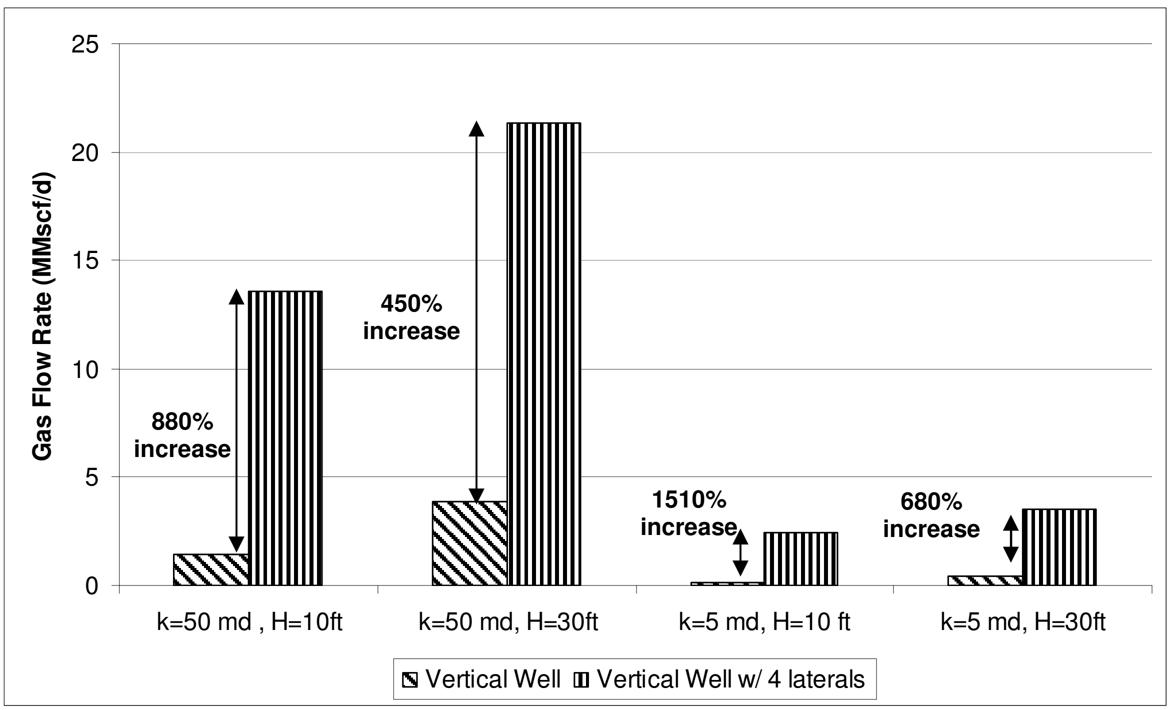

Figure 4-9. Effect of varying reservoir height on stimulation results

Figure 4-9 shows the effect of varying the productive height from 30 feet to 10 feet. In a 50 md reservoir, there is a 78% increase in the benefits of the jetted horizontal from a thick to a thin reservoir. Similarly, the stimulation benefit is doubled in a thin reservoir when compared to the stimulation benefits in a thick reservoir The jetted horizontal laterals have better stimulation responses in thin reservoirs.

Effect of length of Horizontal laterals. In this case, four horizontal laterals of 50 and 100 feet each are modeled in a vertical well for a low permeability reservoir with a productive height of 30 feet. **Figure 4-10** shows the percentage increase in production when the well is stimulated with the jetted horizontals for a lower permeability reservoir while **Figure 4-11** shows the percentage increase in production for a higher permeability reservoir.

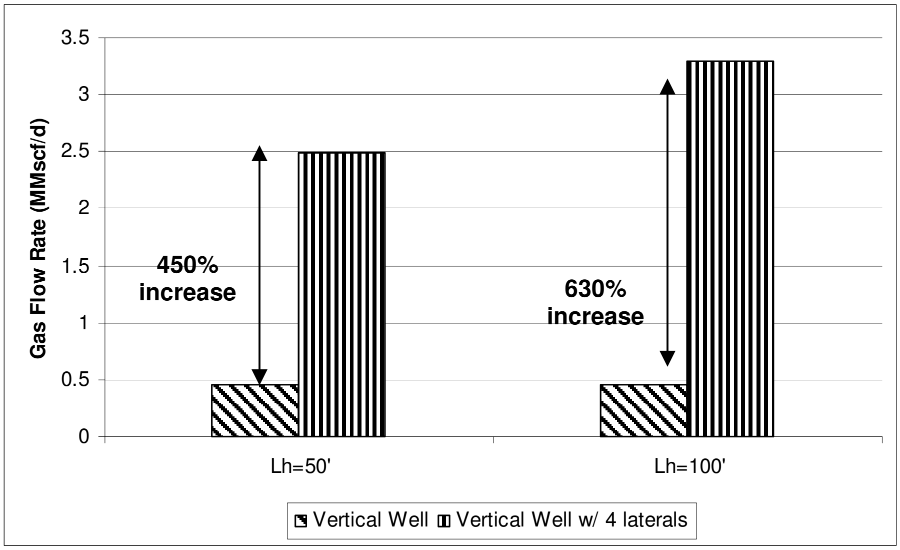

Figure 4-10 Effect of varying lateral lengths on lower permeability reservoir

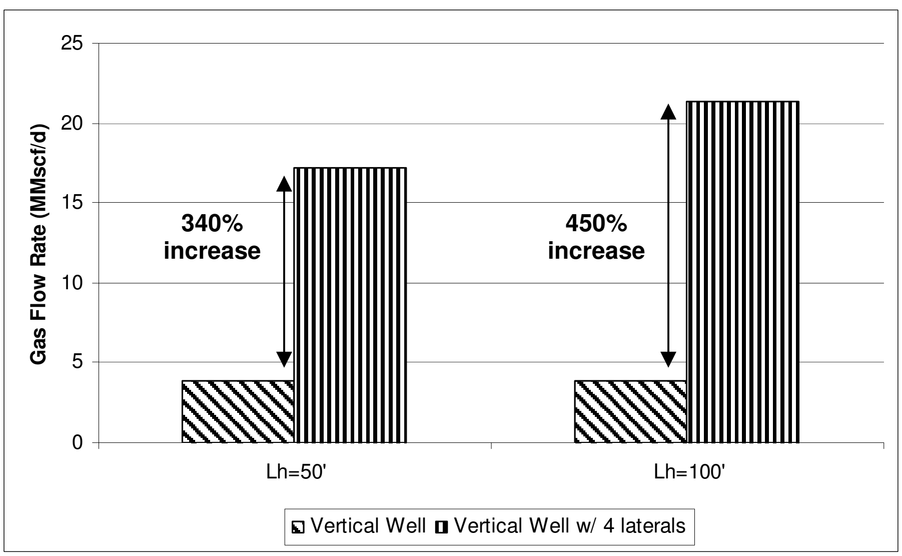

Figure 4-11. Effect of varying lateral lengths in higher permeability reservoir

The stimulation benefit obtained from laterals with a length of 100 feet is higher that the benefit obtained from laterals with a length of 50 feet. There is a noticeable increase in the stimulation benefit obtained from horizontal laterals when the length of the lateral is increased, but there is a better stimulation effect with longer laterals in low permeability formations. Shorter laterals are recommended in higher permeability formations because the incremental benefit obtained through a longer length is likely less than the incremental cost of the added length.

GASGUN™ TECHNOLOGY

Description of Technology

The GasGun™ uses solid propellant, often referred to as a low explosive stimulation technology, to generate high-pressure gas at a rapid rate to stimulate the near-wellbore region. The rate is tailored to the formation characteristics to be rapid enough to create multiple fractures radiating 10 to 50 feet from the wellbore, but not so rapid as to pulverize and compact the rock which results from the use of classic high explosives such as nitroglycerine.

The star-shaped pattern of multiple fractures removes wellbore damage and increases the formation permeability near the wellbore (**Figure 4-12**). The propellant used is similar to that used in large-bore military guns. While the concept of using solid propellants to stimulate oil and gas wells is not entirely new, the GasGun™ incorporates a vastly improved design with progressively burning propellants that have been proven by independent research to be many times more effective in creating fractures and increasing formation permeability.

Application of Technology

GasGun™ stimulations are generally considered to be effective in the following applications:

- Create multiple radial fractures extending 10 to 50 feet from the wellbore. Minimal vertical growth out of pay avoids problems often associated with hydraulic fracturing.
- Remove skin and clean up wellbore damaged by perforators, drilling fines, cement, paraffin, mud cake, scale, etc.
- Stimulate heterogeneous production zones, such as lenticular sands, with a higher probability of success (since fractures reach out in several directions, thus increasing chances of intersecting the producing formations).
- Improve effectiveness of acidizing by fracturing first with the GasGun™, allowing acid to etch new channels into formation.
- Enhance production in naturally fractured reservoirs by intersecting more fractures.
- Prepare wells for subsequent hydraulic fracturing by breaking down formation first with the GasGun™ (treating pressures are often dramatically reduced).
- Improve waterflood efficiency by providing increased and more uniform injection rates

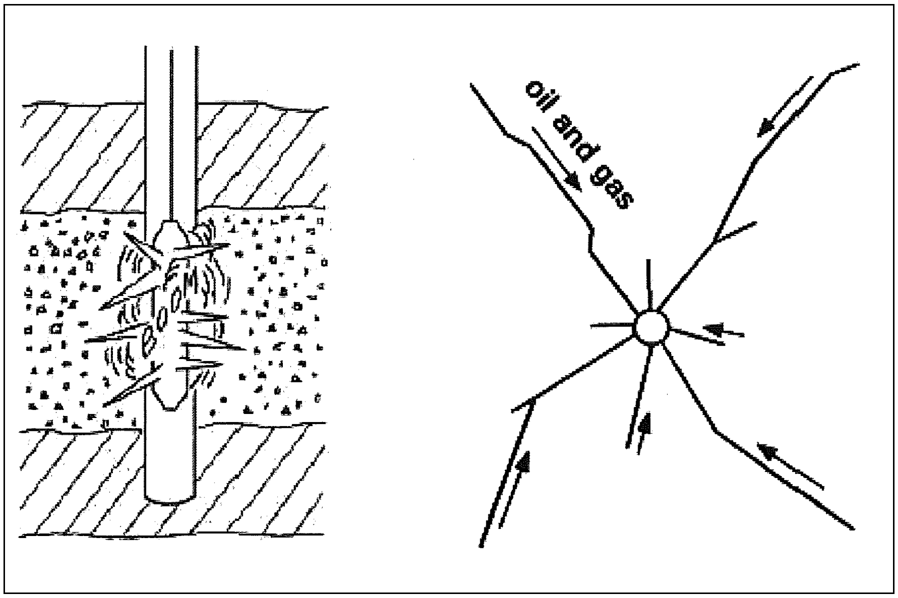

Figure 4-12. Illustration of GasGun Stimulation

Advantages of Technology

Compared to Hydraulic fracturing, GasGun™ has the following advantages:

- Minimal vertical growth out of pay
- Multiple fractures
- Entire zone stimulated — no need to "ball off"
- Minimal formation damage from incompatible fluids
- Homogeneous permeability for injection wells
- Minimal on-site equipment needed
- Much lower cost

The solid-propellant used in the GasGun™ fracturing tool generates high-pressure gases at a rate that creates fractures dramatically different from either high explosives or hydraulic fracturing. The time to peak pressure is approximately 10,000 times slower than explosives and 10,000 times faster than hydraulic fracturing. This leads to multiple fractures that grow radially from 10 to 50 feet, but no more than 2 feet to 5 feet above or below zone. While high explosives crush and compact, a solid propellant produces tensile stress that splits rock, so cavings and cleanup times are minimal. While explosives are limited to open hole, solid propellants can be used in both open hole and perforated pipe. Hydraulic fracturing, on the other hand, creates a single fracture that may wander out of the producing zone, and costs in marginal wells can be prohibitive. Breakout problems to aquifers and thief zones are rare in solid-propellant fracture stimulations using this tool.

Pressure- time profiles for three stimulation methods are shown in **Figure 4-13** below. The time to peak pressure for solid- propellant fracturing using this tool is approximately 10,000 times slower than explosives and 10,000 times faster than hydraulic fracturing.

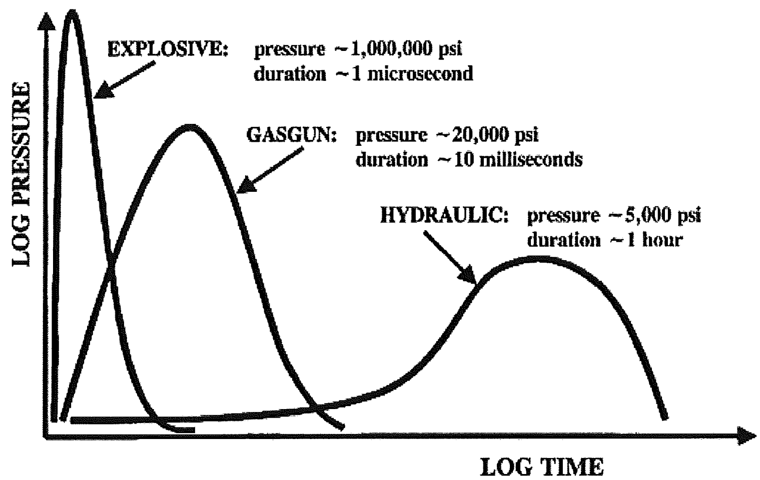

Figure 4-13. Pressure versus Time Profile

ATTEMPTED GASGUN™ FIELD TEST

Introduction

Honeoye Storage Corporation operates an independent gas storage facility located in Ontario County, NY, about 30 miles south of Rochester. The storage zone is a Medina age reservoir found at a depth of 2750 feet, covers an area that is about 12 miles east-west and 6 miles north-south. There are 27 operating wells, 12 observation wells, 19 miles of gathering lines, 2750 hp of compression and a 10.5 mile pipeline running north to the Tennessee Gas and New York State Electric and Gas interconnections. The facility has been operated efficiently for 30 years by a group of six operators and supervisors whose term of employment with the company averages 22 years. As a result of its successful operation over the years, Honeoye has applied for and received authorization from FERC and NY State DEC to increase the maximum stabilized reservoir pressure to 1,100 psia.

Of the 27 injection/withdrawals wells in the field, only three have never been treated with any stimulation technique. In two of these wells the configuration of the completion and bottomhole cement quality pose considerable risk in applying a traditional hydraulic fracturing job.

After researching different stimulation options Honeoye decided that the GasGun™ stimulation is probably the best suited application for these wells since fractures are largely confined to the zone treated. Vertical migration of fractures is typically limited to less than three feet above and below tool.

Storage Well Performance

Honeoye field has 27 injection/withdrawal wells which are periodically cleaned & re-stimulated to maintain/improve deliverability. Two wells proposed for GasGun™ treatments had constrained deliverability due to reduced casing diameters (were reduced when 3.5" tubing strings were place inside the original 5.5 in casings, which suffered corrosion problems). This specific stimulation technology was selected for these 2 wells because the smaller tubing size, weak bottomhole cement quality, and packer configuration prohibited the use of traditional fracturing techniques in these wells.

The following procedures were proposed to be performed in the candidate wells:

Well Stimulation Procedure

a. Run a well test to estimate the pre-test deliverability.
b. Stimulate the wells.

   Mott #3 Well

   1. Suppress the well pressure with water / brine
   2. Run a scraper and gauge ring the length of the tubing to ensure the GasGun™ has the proper clearance
   3. Run the new 10 feet tool with a diameter of 2.75". This tool will fit our wells since the 3.5" tubing has a nominal diameter id of 2.992" with a drift diameter of 2.867".
   4. Buffer the GasGun™ tool with water
   5. Shoot the GasGun™
   6. Swab the tubing and flow back the remaining water to clean out the well

   Weber Well

   1. Suppress the well pressure with water / brine
   2. Pull the 3.5" tubing
   3. Run scraper and gauge ring the length of the tubing to ensure GasGun™ has proper clearance
   4. Run the new 10 feet tool with a diameter of 3.25".
   5. Buffer the GasGun™ tool with water
   6. Shoot the GasGun™
   7. Re-insert 3.5" tubing on packer
   8. Swab the tubing and flow back the remaining water to clean out the well

c. Run a post-stimulation well test to measure the benefits.
d. Analyze and report results.

Difficulties were encountered during implementation of the well stiumulation and well testing phases of this project. Results of the well stimulations and well testing are summarized in Table 4.3 below, and reflect these difficulties. Unfortunately, due to the operators budgetary constraints, the operator could not secure the funds necessary for additional stimulations and testing.

UGS well	Pre-Stimulation Well Test	GasGun Stimulation	Post-Stimulation Well Test
Mott # 3	☒ not obtainable	☒ attempted - failed	☒ attempted - no data
Ouellet # 1	☑ data obtained	☒ not stimulated	☒ no data
Weber #15	☑ data obtained	☑ successful	☑ data obtained

The Mott #3 well had no stimulation pre-stimulation data because the well became inoperable prior to implementing the stimulation. The well was deepened during a later workover operation and then stimulation was attempted using the GasGun technology. The stimulation was unsuccessful due to a blow out. Post-stimulation testing was attempted but no data was obtainable. The Mott #3 well was inoperable for well testing.

The Ouellet #1 well was then chosen to replace the original test well (Mott #3) as a field test candidate. Although Ouellet #1 had pre-stimulation well test data available and was a feasible candidate for the project, the well could not be stimulated due to operational problems that arose. Since the well was not stimulated, there was no reason to run a post-stimulation well test.

Backpressure plots are used to evaluate the effectiveness of a stimulation treatment by comparing the deliverability of the well prior to the stimulation treatment to the deliverability of the well after the stimulation treatment. **Figure 4.14** shows the results of the Ouellet #1 pre-stimulation test (solid line) as well as a synthetic line (dashed line) to illustrate the shift that would occur if a successful stimulation treatment was performed. If the well is successfully stimulated, the deliverability line is expected to shift towards the right.

==Use “generic” plots to demonstrate analysis procedure, not Ouellet well - Can still show Ouellet well plot, but don’t use it to explain theory. Also, remove synthetic data from Ouellet plot if you show it ===

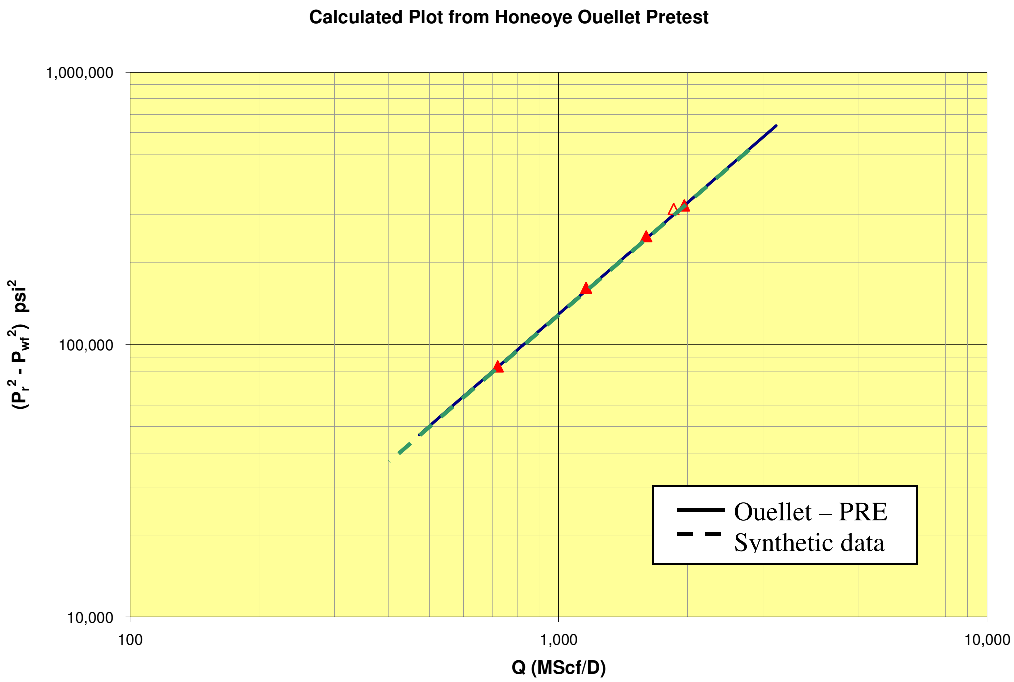

Figure 4-14. Backpressure Plot from Heneoye Ouellet Pretest

The Weber #15 well was stimulated successfully following the proposed procedure. Both pre-stimulation test data and post-stimulation test data were obtained and analyzed (**Figure 4-15**).

The deliverability curve shifted towards the left after the stimulation, suggesting that the stimulation had a slight negative effect on the well deliverability. Although the data set obtained from this test well is complete, results from one single well cannot be used as a basis for analyzing the effectiveness of the GasGun™ stimulation technology in comparison with other stimulation methods in underground gas storage wells.

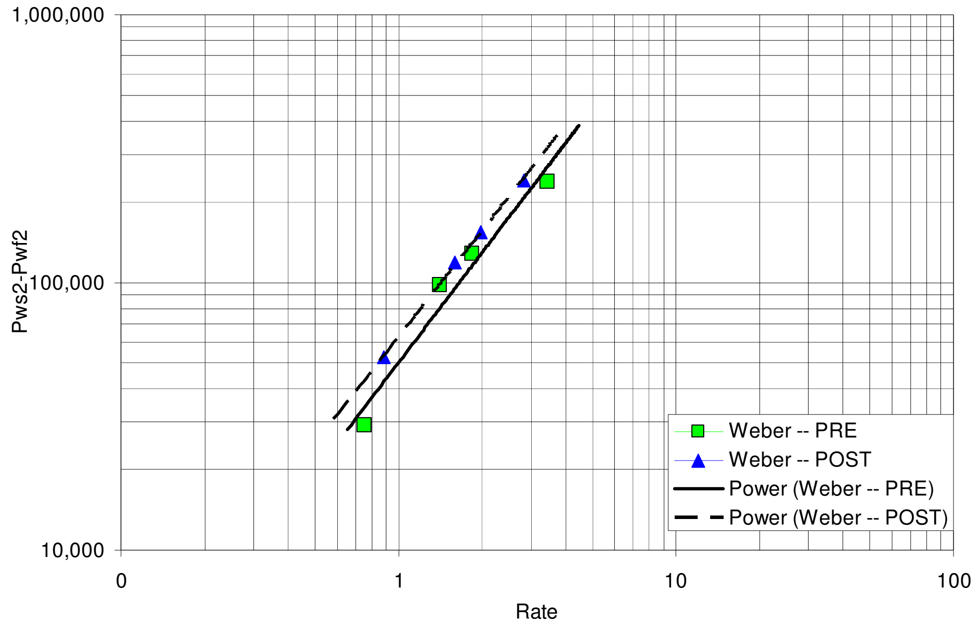

Figure 4-15. Backpressure Plot from Weber Pre-stimulation and Post-stimulation Test

In our opinion, we feel that we could have achieved better results had we obtained complete field study datasets from at least 3 wells (complete data sets from more wells would be preferable). The possibility of operational complications in well testing and GasGun stimulation should have been considered, as well as the additional costs associated with failed attempts to stimulate and test. In this case, the pilot study should have been planned for at least 6 suitable wells. If the number of test wells is increased, it would become even more difficult to obtain the participation of industry operators and the cost of the study would be significantly higher.

In light of the difficulties encountered, further attempts to perform a field pilot study were abandoned. Nonetheless, in order to evaluate the effectiveness of the GasGun™ technology, public domain data showing stimulation results from several wells in various locations were obtained and analyzed.

Results of Evaluation

The GasGun™ technology data was obtained from various data sources such as the Petroleum Technology Transfer Council (PTTC)[12], The GasGun™ website[11], Petroleum Tech digest and GasGun™ client data. The analysis was based on a sample size of 175 wells that had been stimulated using the GasGun™ technology.

The GasGun™ successes and production rate increases were investigated for various wells and the results were analyzed in the following categories:

- Formation type
- Location
- Well depth
- Perforation length
- Location
- Data source
- Reservoir fluid type
- Well type

From the data set obtained, there is an overall 80% chance of success with the GasGun™ stimulation procedure and an average of 250% increase in production for the wells. **Figure 4-16** shows the success of the stimulation according to the type of reservoir fluid in the well while **Figure 4-17** shows the production rate increase for the wells according to the reservoir fluid type.

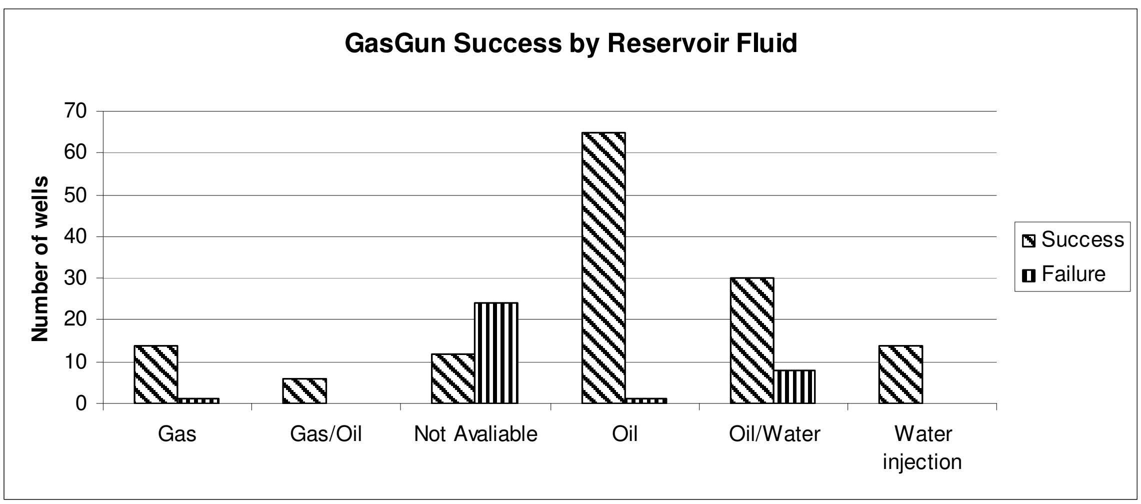

Figure 4-16. GasGun™ Success by Reservoir Fluid

A large amount of the sample data were for stimulation in oil producing wells and only 15 wells out of 175 wells sampled are in gas production wells. Nonetheless, the trends observed in oil production well GasGun™ stimulations can be applicable to the underground gas storage wells.

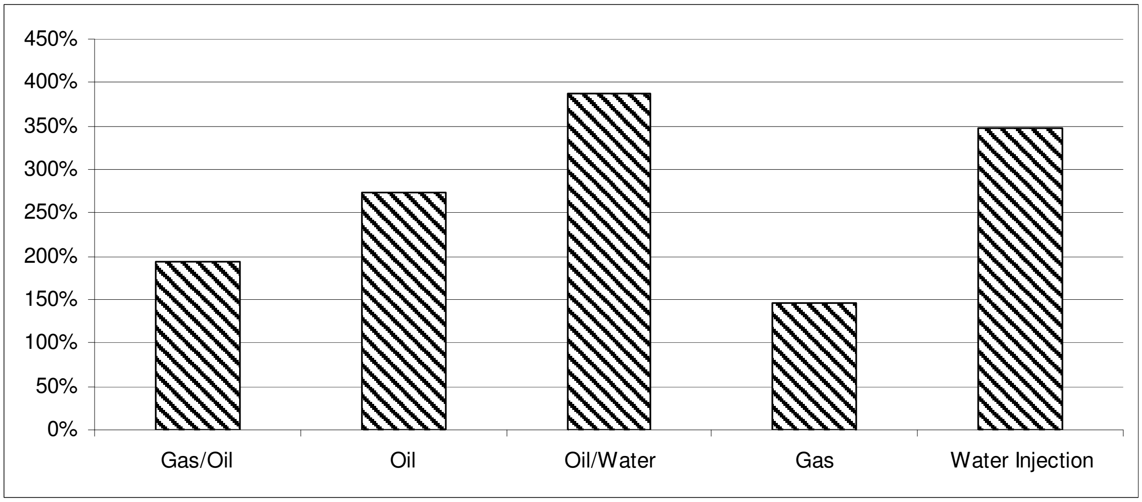

Figure 4-17. Average Well Production Rate Change by Fluid in Reservoir

The trend observed in **Figure 4-17** indicates that the increase in production observed in gas wells after GasGun™ stimulation is generally less than the increase in production observed in oil producing wells. The presence of produced gas in the oil tends to reduce the stimulation effectiveness.

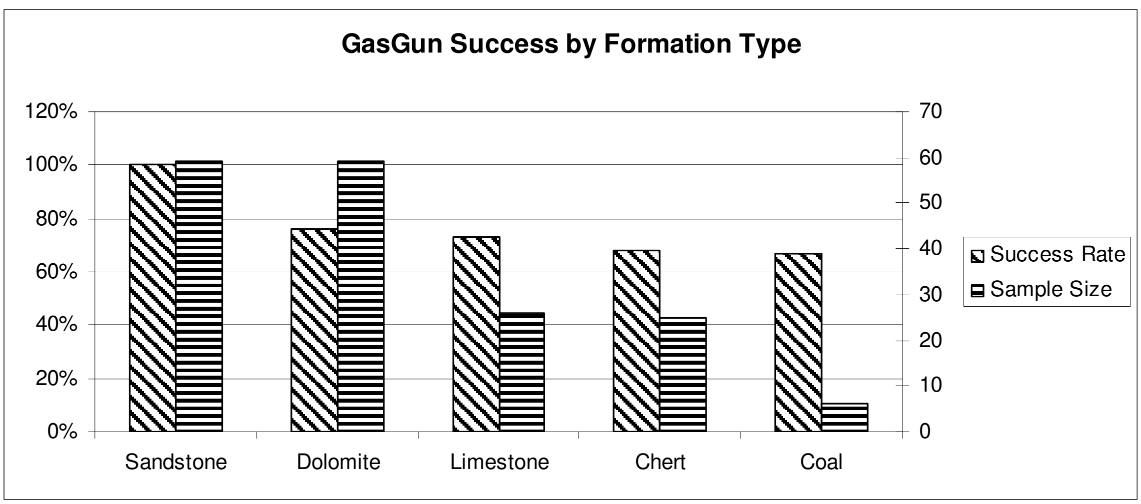

Figure 4-18. GasGun™ Success by Formation Type

Figure 4-18 shows the success rate of the GasGun™ technology by formation type. The success rate of the GasGun™ technology in sandstone formations is very high and the sample data shows a 100% success rate. The success rate is lower in carbonate and chert formations.

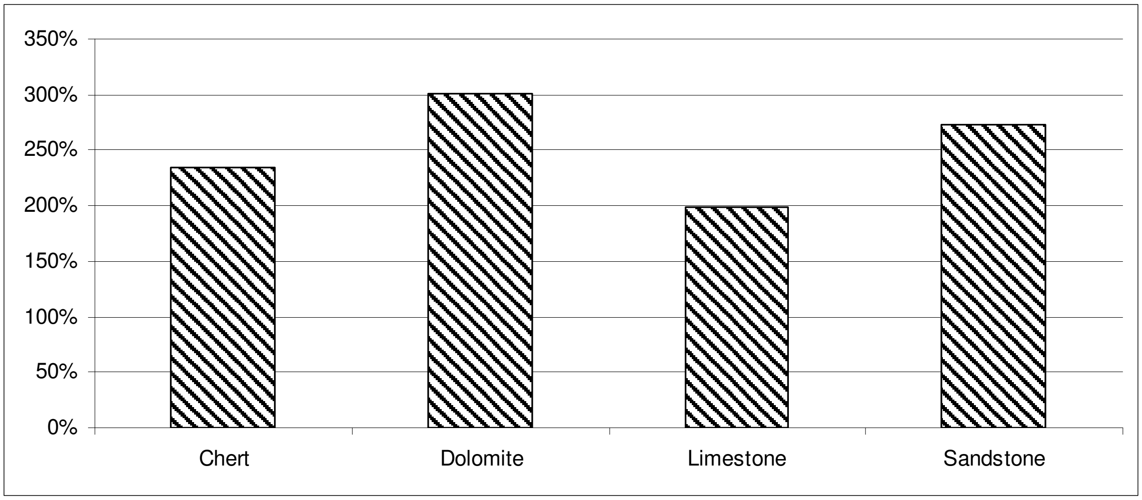

Figure 4-19. Oil Well Production Rate Change by Formation type

Figure 4-19 shows oil well production rate change by formation type. The results of a GasGun™ stimulation does not seem to be affected or enhanced by the formation type. **Figure 4-19** shows that various formations experience a relatively similar increase in production. However, GasGun™ stimulation may be used in limestone and dolomite formations prior to an acidizing treatment to increase the effectiveness of the treatment and to allow the acid to etch new channels in the formation.

Figure 4-20 shows gas well production rate change by formation type, and suggests that using GasGun™ technology to stimulate a chert or dolomite formation may be slightly more effective that in a sandstone.

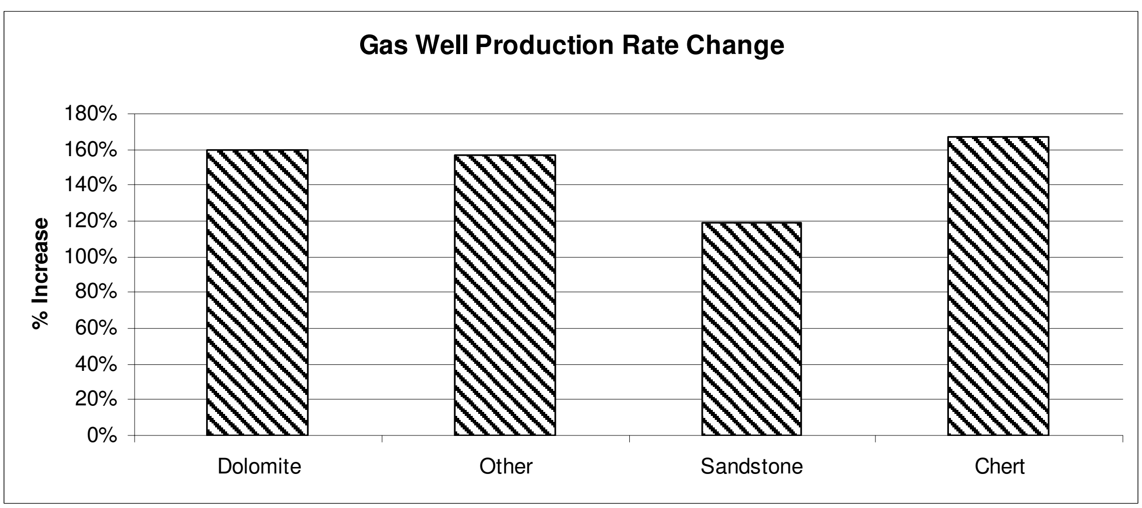

Figure 4-20. Gas well Production Rate Change

Figure 4-21 shows the gas well production associated with cased hole and open hole completion types.

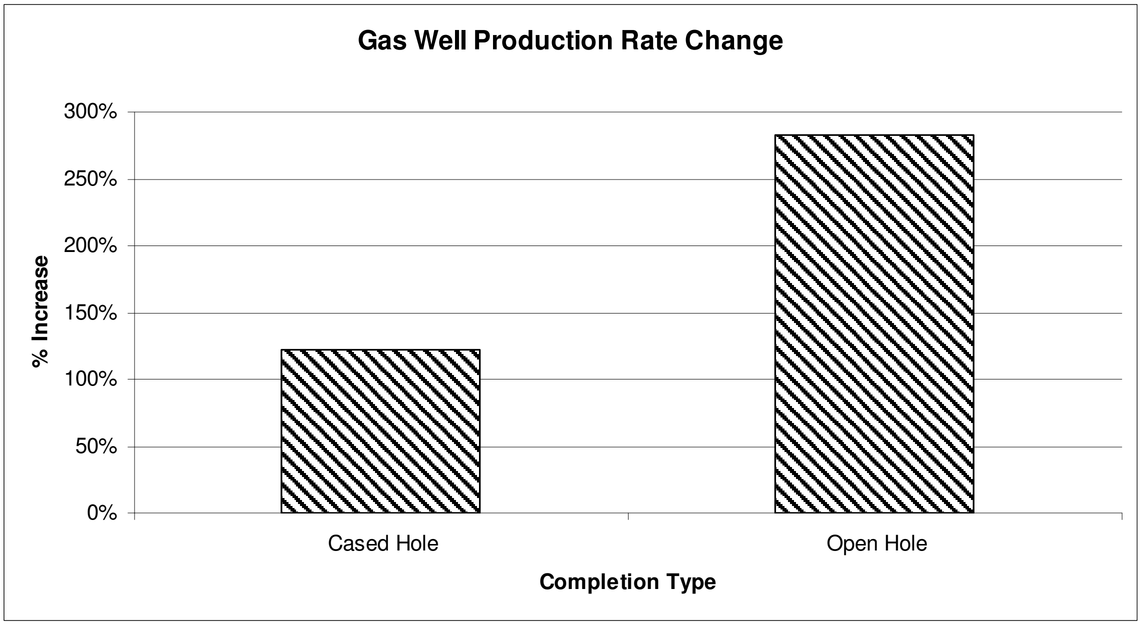

Figure 4-21 Gas Impact of Completion Type on Well Production Rate Change

Figure 4-22 shows the impact of well depth on the gas well production improvement.

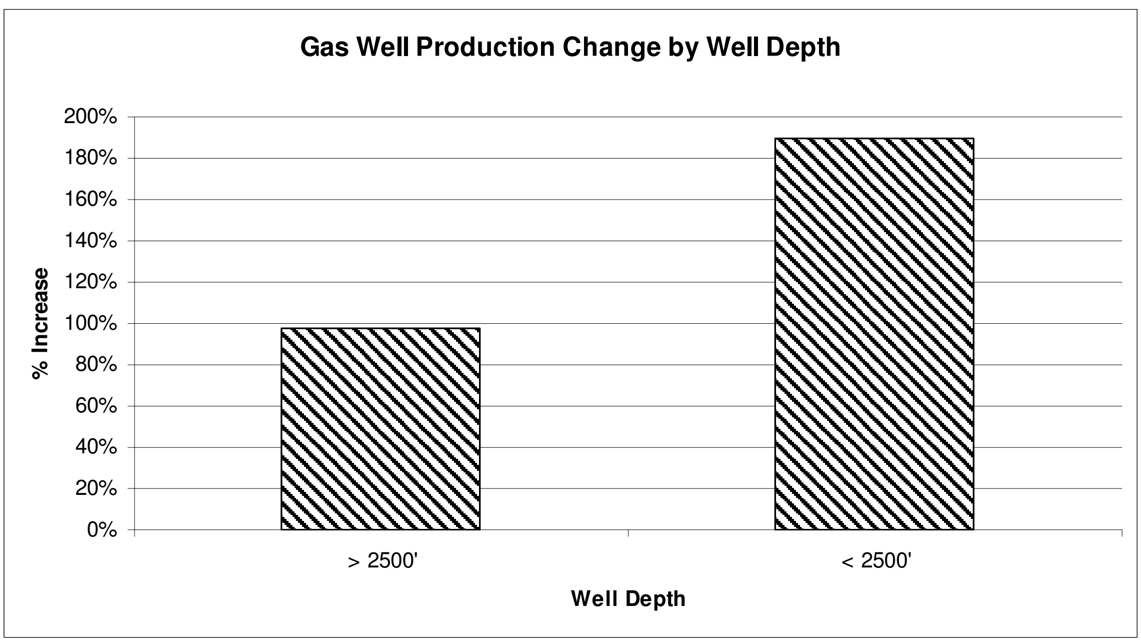

Figure 4-22 Impact of well Depth on Gas Well Production Change

Figure 4-23 shows the gas well production change associated with different perforation lengths.

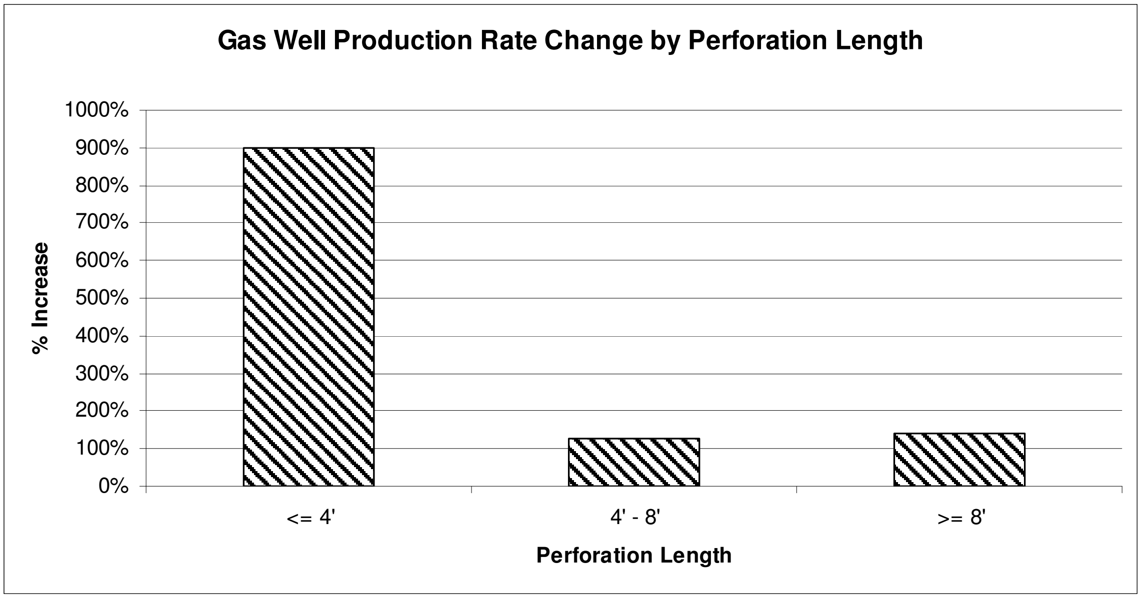

Figure 4-23 Impact of Perforation Length on Gas Well Production Change

Figure 4-24 shows the gas well production change associated with different well locations.

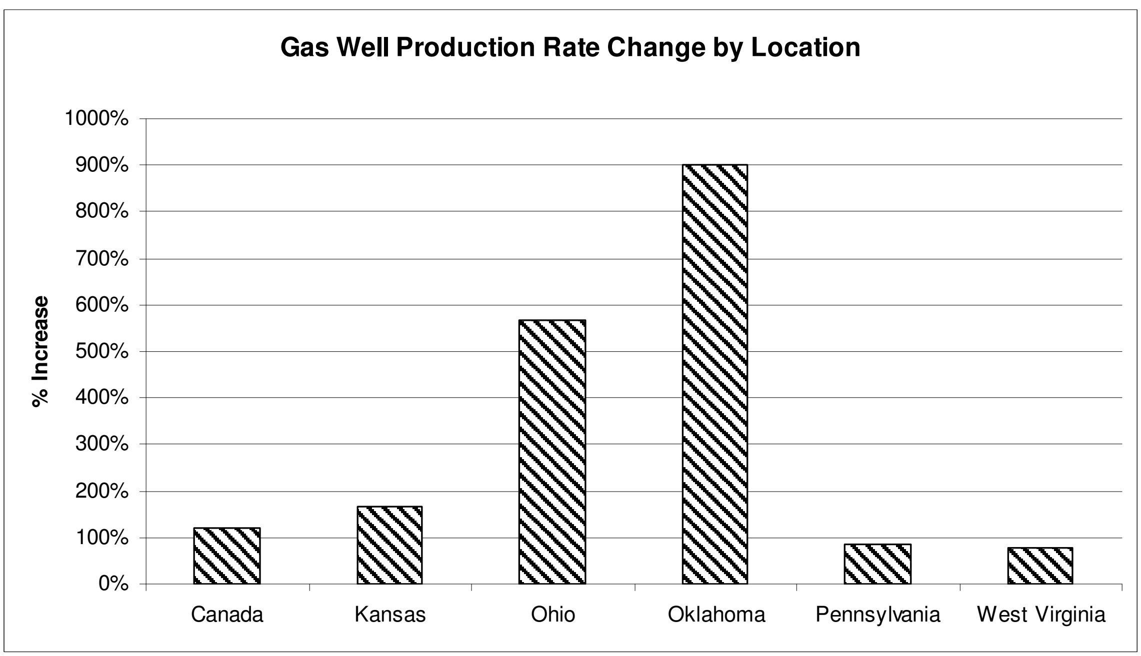

Figure 4-24 Impact of Location on Gas Well Production change

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[12] Petroleum Technology Transfer Council, "PTTC.org" http://www.nmcpttc.org/Case_Studies/Gasgun